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RADON EXHALATION FROM URANIUM MILL TAILINGS PILES -
DESCRIPTION AND VERIFICATION OF THE MEASUREMENT METHOD

D. E. Bernhardt, et al

Office of Radiation Programs
Las Vegas, Nevada

November 1975

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D. E. Bernhardt

F. B. Johns

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NOVEMBER 1975

OFFICE OF RADIATION PROGRAMS - LAS VEGAS FACILITY
U.S. ENVIRONMENTAL PROTECTION AGENCY
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MILL TAILINGS PILES

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of the Measurement Method

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November 1975

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PREFACE

Uranium mills are a part of the nuclear fuel cycle designed to extract uranium from ore which contains radioactive isotopes of the naturally-occurring uranium series decay chain. These isotopes, some of which are extremely long lived, are discarded as mill wastes into large ponds and tailings piles. Wind and water erosion have scattered the mill wastes over large parts of the mill sites' local environs, resulting in land contamination and increased population radiation exposure. Releases of radon-222, the noble gas progeny of radium-226, from the tailings piles can result in an inhalation dose to people in adjoining areas.

This study was made in cooperation with the Energy Research and Development Administration to evaluate existing conditions at inactive uranium mill sites in order that appropriate remedial actions can be taken to decontaminate the site environs, minimize erosion, and reduce population exposures.



Donald W. Hendricks

Director, Office of
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RADON EXHALATION FROM URANIUM MILL TAILINGS PILES
Description and Verification of the Measurement Method

Abstract

Uranium mill tailings piles result in several sources of radiation exposure. These exposures are primarily from concentrations of the uranium progeny, thorium-230, radium-226, and radon-222, in the tailings. Radon-222 and its progeny are a source of external gamma and lung exposure.

Using the accumulation technique, field measurements of the radon flux from uranium mill tailings were made at three mills and at one experimental plot. The sample collection technique, method of calculating results, and reproducibility of the technique are described.

The exhalation data ($\text{fCi/cm}^2\text{-sec}$) reveal that reproducibility is within about 10 percent and that the variation is less than the uncertainty associated with the linear regression analysis of the accumulated radon concentration versus time. Long term measurements (greater than about 8 hours) result in accumulated concentrations that approach the radon concentrations in the surface soil gas, and invalidate the assumptions inherent in the accumulation technique.

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Funding for this study was provided in part by the Office of Energy, Minerals, and Industry, USEPA Office of Research and Development.

INTRODUCTION

Uranium mill tails are natural materials which have been manipulated by man. The uranium ore is removed from its original geological setting by standard mining techniques. At the mill site the ore is crushed and treated with acid or basic solutions to remove uranium and other metals. Organic solvents are also used in the processing. The fine particulate (micrometers to millimeters in diameter) waste material and the bulk of the ore, along with spent solvents and process water is transferred to tailings ponds and piles which are in direct contact with the biosphere.

The tailings contain about 10 percent or less of the original uranium isotopes, plus elevated concentrations of the progeny of uranium, notably thorium-230 and radium-226. The milling process is very selective for uranium, thus the progeny radionuclides are in concentrations equivalent to the original ore content of uranium (0.1 to 0.5% U_3O_8). The progeny concentrations range up to about 3000 pCi/g with nominal values around 1000 pCi/g, or roughly 1000 times normal average background concentrations.

Radionuclides in the tailings are in contact with the biosphere and present several sources of radiation exposure for man. This report is concerned with radon-222, the noble gas progeny of radium-226.* The inhalation of airborne progeny

*References in this report to radium and radon refer to radium-226 and radon-222, respectively, unless otherwise indicated.

of radon, resulting from radon diffusion or exhalation from uranium mill tailings, result in a lung dose to man. There is an additional dose to other organs as a result of transfer of material from the lungs to the blood and lymph systems. Several studies of ambient radon concentrations around mill tailings piles (Snelling, 1971; Shearer et al., 1969; Duncan and Eadie, 1974; and more notably Swift et al., in press) characterize the inhalation dose from radon progeny as being among the highest doses to man from uranium mill tailings piles. This is especially true for piles where stabilization efforts to reduce erosion by wind and water have been made.

Scope of Study

There appears to be no previously reported data on the radon exhalation rate or ($\text{fCi}/\text{cm}^2\text{-sec}$) from uranium mill tailings piles.* This report describes the equipment and technique used in a recent field study to measure the flux from three inactive uranium mill tailings piles. Measurements were also made on a laboratory test plot. The calculation techniques and data which verify the sampling technique are presented. Correlation of the radon flux with the various uranium mill tailings pile parameters (e.g., radium concentration, moisture content, and porosity) will be discussed in future papers.

*A private communication in October, 1975, with Mr. Andreas George of the Energy Research and Development Agency, Health and Safety Laboratory, indicates they made flux measurements on the Edgemont, South Dakota pile in the summer of 1975.

Several techniques for measuring the radon flux are reported in the literature. Pearson (1967) reports sampling the radon from a stream of air flowing across the ground-air interface. Megumi and Mamuro (1972) present a technique where radon is directly accumulated in a bed of granular activated charcoal placed on the soil surface. The technique used in this study is similar to that used by Wilkening et al. (1972). Radon is accumulated in an open faced vessel inverted and placed on the surface and periodic aliquots of the accumulated mixture are taken for analysis of radon.

The validity of the accumulation method is based on several assumptions:

1. The accumulation time must be short compared to the half-life of radon or else decay corrections must be made.
2. The concentration of radon in the accumulator must remain significantly below the soil gas concentration. Otherwise, back diffusion will occur and the vertical soil profile of the radon concentration will change. Wilkening et al. (1972) suggest that the accumulated concentration be kept below 10 percent of the soil gas concentration at a depth of 13 cm, as noted by Kraner et al. (1969).
3. The accumulator must be emplaced so as not to disturb the soil.

EXPERIMENTAL PROCEDURES

Technique

The sampling technique was based on measuring the increasing radon concentration in an open-ended barrel, placed open-end down on the tailings. Figure 1 is a schematic of the sampling system.

The sampling or accumulation vessel was a barrel, with one end removed. The bead or barrel rim was left on to provide support for the barrel on the tailings surface. Both 30- and 55-gallon barrels were used in the field study. Two one-quarter inch diameter connections were welded to the side of the barrels, and one was located on top. These

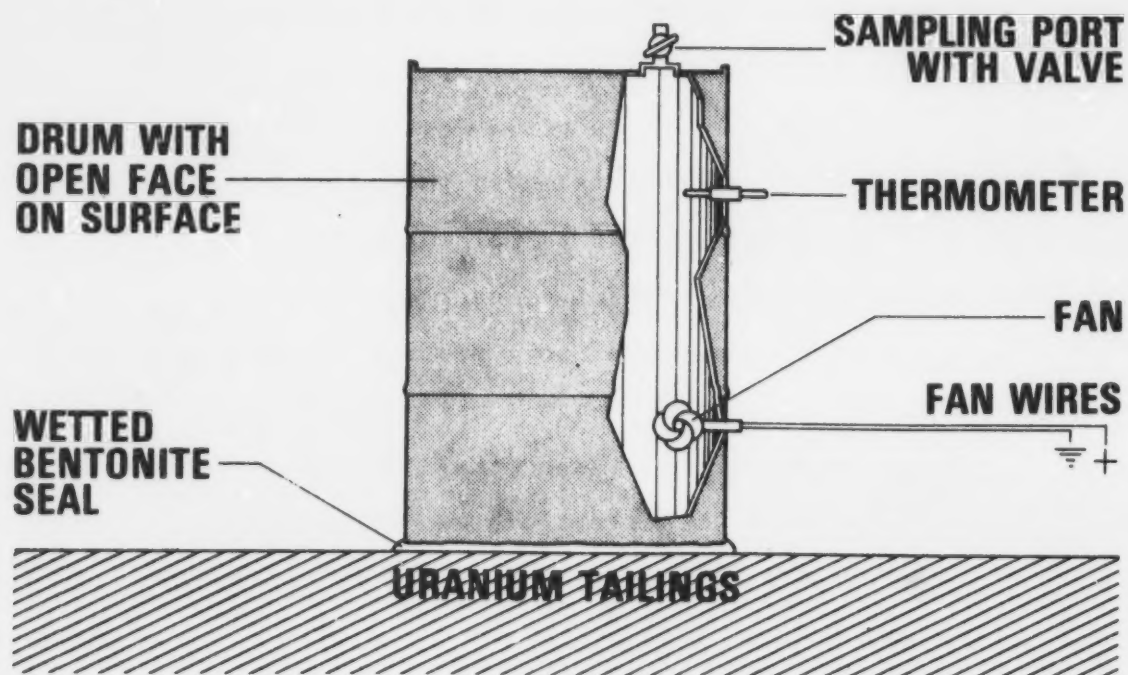


Figure 1
Radon Accumulation Vessel

were used for sampling ports, to measure the temperature inside the barrel, and to route wires for a fan which insured mixing of the gases.

The use of the sample ports varied. In several instances concurrent samples were taken from the top and bottom ports to determine if gases in the barrel were mixed. The temperature of gases in the barrel was monitored by inserting a glass thermometer into the barrel through one of the ports. For several experiments a 12-volt fan was mounted inside the barrel to insure mixing of the air and exhaled radon. Caulking material was used to seal the thermometer and wiring ports.

Temperature fluctuations of the gases in the barrel result in associated pressure or gas volume fluctuations. Although the barrels were originally painted with aluminum paint to reflect solar radiation, measurements during the initial experiments indicated temperature increases of up to 8°C. Additional temperature control was accomplished by utilizing evaporative cooling from wet towels placed on the barrel. This limited the difference between the ambient and the barrel temperature to several degrees Centigrade. The final technique involved wrapping the barrel (top and sides) with 2.5-cm foam rubber and covering it with a "space blanket" (combination of aluminum foil and mylar layers). This technique was independent of relative humidity and provided adequate temperature control (about 1°C).

After selecting a location on the pile with a flat, continuous (non-cracked) surface, the barrel was carefully

placed on the pile surface. As emphasized by Pearson (1967), efforts were made not to disturb the surface. Areas with large rocks which would reduce the effective diffusion area were avoided. The vessel was sealed to the surface by sprinkling dry bentonite around the edge of the barrel. The bentonite was then moistened to provide a wet clay seal. Analysis of the bentonite indicated a radium-226 content of 2.5 pCi/g.

After the barrel was emplaced and sealed on the surface, a minimum of four samples of the air/radon mixture were taken at approximately one-half hour increments. Sampling periods of up to 12 or even 48 hours were used in several instances. Samples were taken from the top port through a filter holder into an evacuated scintillation cell. The filter holder contained a valve for closing the sampling train, and a 0.45 micrometer filter for removal of the radon progeny and any dust. Prior to taking samples, about 100 ml of air were withdrawn to remove stagnant air from the sampling train and to insure that the sample would be representative of the air/radon mixture in the barrel. Connections between the scintillation cell and the sample train consisted of flat glass joints, a rubber O-ring, and a spring clamp. Radon progeny were allowed to accumulate in the cells for about four hours prior to counting. The ingrowth half-life is 30 minutes; thus, 4 hours allows for 99.6 percent of equilibrium.

The scintillation cells were similar to those described by Lucas (1957). Scintillations from alpha particle interactions

with the zinc sulfide coating inside the cell were counted through the end window of the cell, on a photomultiplier (PM) tube. The cells, which have a volume of 125 ml, were evacuated and purged with nitrogen or aged air at the laboratory prior to use in the field. In the field the cells were alternately evacuated and purged with ambient air for a period of an hour prior to reuse. These techniques removed the alpha emitting progeny, thus minimizing the background counting rate.

Sample Analysis

The counting instrument consisted of a 5-cm (2-inch) diameter PM tube and preamplifier mounted in a counting chamber. A Ludlum Model 20 scaler provided high voltage, low pulse-height noise discriminator, time, and scaler functions. The counting chamber was sealed to prevent the influx of light during counting. Safety switches insured that the high voltage was turned off when the chamber was opened.

The counting equipment was operated in a darkened room to minimize the impact of potential light leaks. Fluorescent room lighting was not used, thus minimizing the photon activation of the scintillation cells.

Scintillation cells were placed directly on the PM tube. After turning on the high voltage there was a delay of several minutes prior to counting the sample, to insure decay of any photon (light) activation of the scintillator and to allow stabilization of the high voltage.

Calculations

The data were transformed from observed counts per minute to exhalation-rate in $\text{fCi}/\text{cm}^2\text{-sec.}$ These calculations are described in the following three sequences:

- Conversion of the counts per minute in the scintillation cell to $\text{pCi}/\text{l.}$
- Regression analysis of pCi/l as a function of time
- Conversion of $\text{pCi}/\text{l-min}$ in barrel to radon flux in $\text{fCi}/\text{cm}^2\text{-sec.}$

Samples of the air/radon mixture were taken in evacuated scintillation cells and counted on a PM tube after allowing for ingrowth of the progeny. The results, in counts per minute, were converted to pCi/l at standard temperature and pressure by use of an empirical cell factor ($1.7 \text{ pCi}/\text{l}$ per count per minute) and corrections for temperature and pressure differences. More details are given in Appendix A.

Lucas and Woodward (1964) note that the disintergrations from the radon progeny do not meet the assumptions necessary for the validity of the normal distribution (variance equal to the number of counts). Their tabulation of correction factors indicates that for counting intervals of about one hour and a counting efficiency of 70 percent, the variance is 1.624 times the number of radon and progeny counts. The 95 percent confidence interval counting error is about 2.5 (1.3×1.96) times the square root of the number of counts.

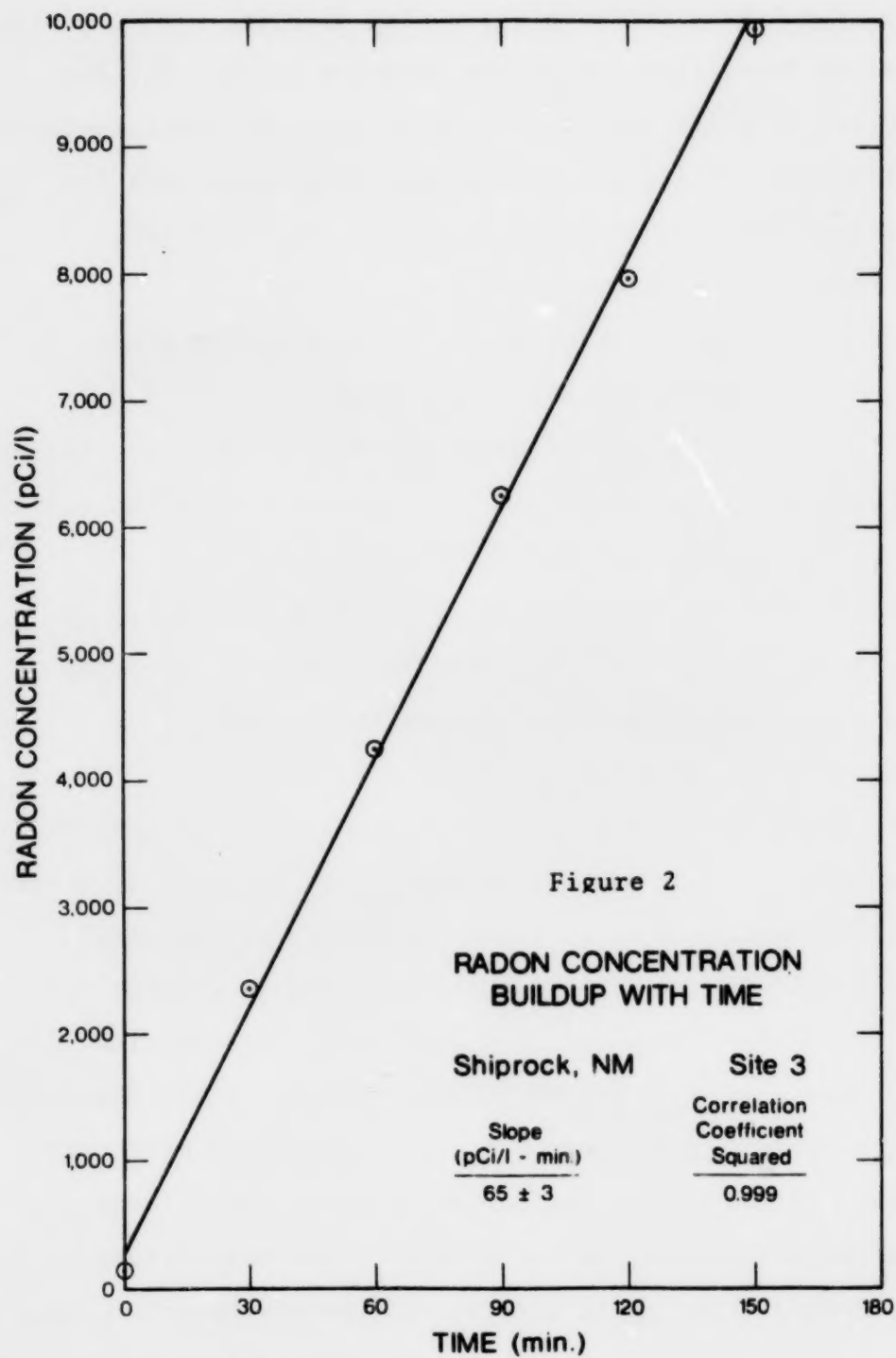


Figure 2 is a representative plot of data, with a linear regression line, from one of the sampling sites. The data is plotted as pCi/l versus time after starting the accumulation in the barrel. There are several possible techniques for calculating the rate of build-up of the concentration.

These include:

- A regression analysis of the data; i.e. the slope of the regression line (pCi/l-min).
- The change in concentration divided by the accumulation time; e.g. concentration at 30 minutes minus the initial concentration, divided by 30 minutes.

The "difference method" provides a build-up rate for each sampling interval. But, the calculated rate is dependent on the selection of the accumulation time period: e.g., starting time to 30 minutes, or 30 to 60 minutes.

If the accumulation or sampling time is short compared to the half-life of radon (3.83 days), the build-up is linear and can be expressed by a linear regression of the data (pCi/l versus time). This results in a single average value for a set of measurements. For each case, the validity of the linear regression approach is limited to the assumption of steady-state conditions; i.e., the parameters affecting the flux did not change during the sampling time. These parameters include the moisture content and temperature of the medium (soil or tailings), and the atmospheric pressure. Although there were undoubtedly minor changes in some of these

parameters, it is concluded that the linear regression line, with the radon concentration as the dependent variable, is an adequate representation of the radon flux. The equation for the regression line is:

$$y(\text{pCi/l}) = a (\text{pCi/l}) + b (\text{pCi/l-min}) \cdot X (\text{min})$$

Where:

y = the dependent variable, radon concentration in pCi/l.

a = the intercept of the regression line in pCi/l.

b = the slope of the regression line in pCi/l-min.

X = the time of accumulation in min.

In addition to the regression coefficients, error terms for the slope and intercept, and the correlation coefficient of the regression line were calculated. The error term for the slope indicates the uncertainty of the slope based on the scatter of the data and the number of data points. The correlation coefficient squared, r^2 , is the proportion of the variance of the values of y explained by the linear regression on x.

The error term for the intercept indicates its significance. Given the basic assumptions that the initial radon concentration in the drum was zero, that the site was not disturbed when emplacing the barrel, and that the linear regression is valid, the intercept should be zero.

The calculations were done using standard equations, such as those indicated by Natrella (1963), Riggs (1968),

and Remington and Schork (1970). Additional information on the calculation of error terms is given in Appendix A.

The radon exhalation flux (fCi/cm^2 -sec) is calculated as the product of the concentration build-up rate (pCi/l-min) and the ratio of the volume and cross-sectional area of the sampling container. Table 1 summarizes these values for the two containers (55- and 30-gallon barrels) used in this study.

Table 1
Radon Flux Calculation

Container	Volume (liters)	Cross Sectional Area (cm^2)	$\frac{fCi/cm^2 \cdot sec}{pCi/l \cdot min}$
55-gallon	209	2420	1.44
30-gallon	120	1690	1.18

The following equation was used to calculate the values in the right hand column of Table 1.

$$\frac{pCi}{l \cdot min} \times \frac{\text{Barrel volume in l}}{\text{Barrel area } cm^2} \times \frac{min}{60 \text{ sec}} \times \frac{10^3 fCi}{pCi} =$$

$$\frac{fCi/cm^2 \cdot sec}{pCi/l \cdot min}$$

RESULTS

Figure 3 is a bar graph summarizing the radon flux values from field studies at three uranium mill tailings sites and from test plots at the Boulder City, Nevada, U. S. Bureau of Mines facility. This report focuses on the validity and reproducibility of the measurement method. Interpretation of the results, based on variations of pertinent parameters, will be the subject of subsequent reports. All of the radon exhalation flux values and intercepts, duration of sampling periods, and error terms are included in Appendix B.

The counting error for the radon analyses was generally less than 5 percent for the first sample (lowest quantity of radon) and less than 2 percent for subsequent samples. Thus, in most instances the variation due to the counting statistics has a minor impact on the total variation of the results.

An additional analytical error stems from the use of a common cell factor (pCi/1 per count per minute). The significance of this error can be evaluated from the data in Table 2. The percent difference of the results averages about 5 percent and is somewhat higher than the counting errors (generally 1 percent). Aldrich et al. (1975) report a standard error of about 6 percent for the calibration or cell factor of six cells. Although this error is greater than the counting error, the overall significance is limited.

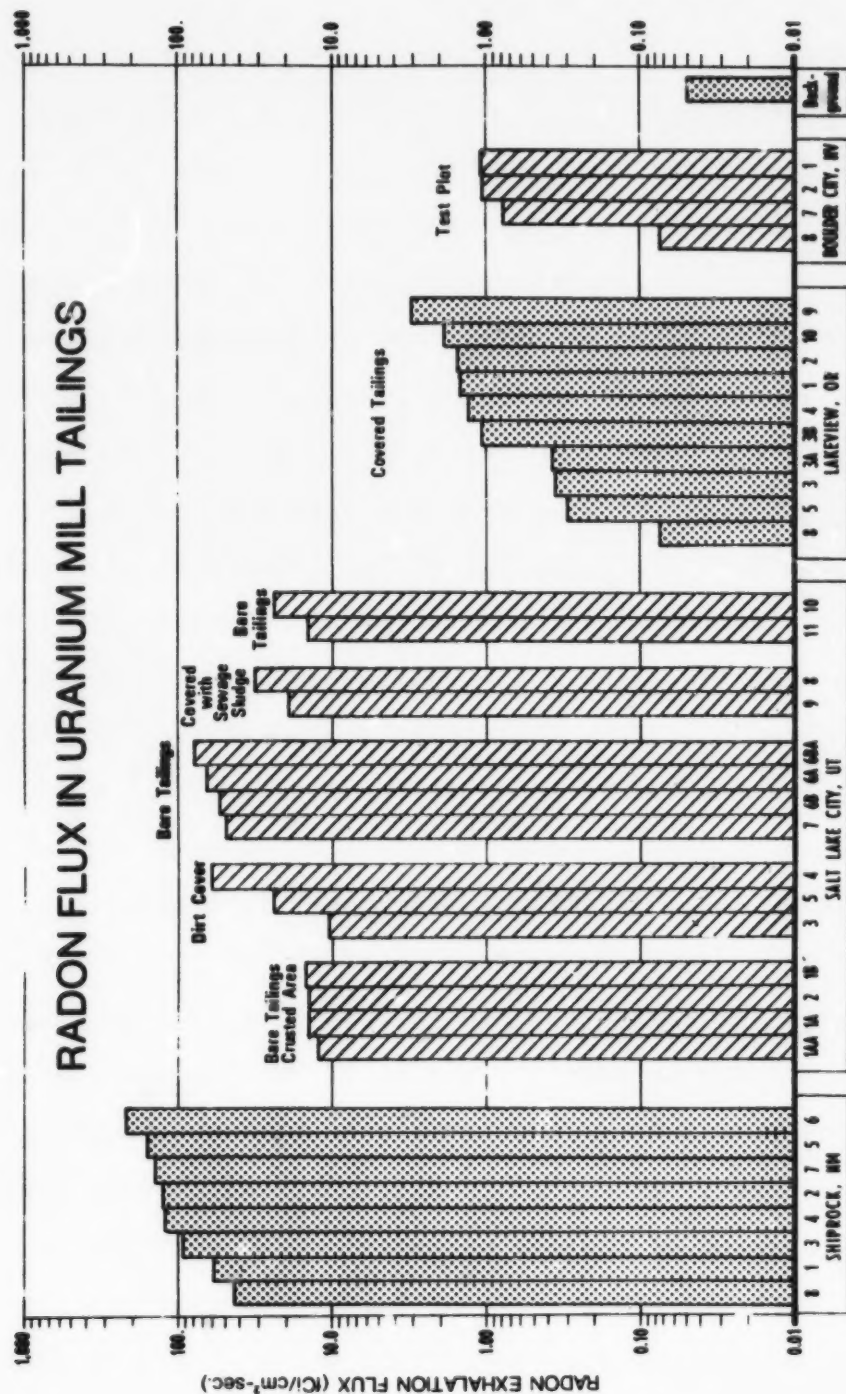


Figure 3

TABLE 2
Replicate Radon Samples
(Errors at 95 Percent Confidence Level)

Series	Radon Conc. (pCi/l)	Counting Error (pCi/l)	Average	Percent Difference From Average
Salt Lake City				
6B-1	32,000	280	32,000	
	32,000	280		
6BA-1	3,800	59		
	3,400	57		
	3,600	58	3,600	6
6BA-2	5,000	68		
	5,100	73		
	5,400	71	5,170	4
6BA-3	7,300	82		
	6,900	81	7,100	3
6BA-4	7,500	83		
	7,300	83	7,400	0.1
6BA-5	10,000	98		
	11,000	100	10,000	5
Lakeview				
10-1	300	11		
	260	11	280	7
Boulder City	230	2.3		
7	200	6.8	215	7
8	13	1.7		
	16	1.9	14.5	10

Several tests were conducted to insure that the gases in the barrel were thoroughly mixed. The difference between samples taken from the top and bottom sampling ports was less than 5 percent and less than the 2-sigma counting error. Samples taken before and after operation of the fan during daytime hours also indicated insignificant differences. One set of samples taken at night, before and after mixing with the fan, indicated the possibility of incomplete mixing.

It appears that solar heating of the barrel insures self-mixing. Mechanical mixing appears to be prudent to insure mixing of the gas volume prior to taking samples at night.

Replicate sample results are presented in Table 3.

These samples were taken over the exact same area, or within about 2 meters of each other, in areas where the tailings had uniform physical and chemical characteristics. Agreement within the 95 percent CL error of the regression line attests to the reproducibility of the method within the stated regression error. These values further indicate reproducibility not only with sequential measurements using one barrel, but also with barrels of different sizes.

Three measurements were made at Salt Lake City Site 1. Simultaneous measurements were made on two plots one meter apart (1A and 1B). The 30-gal. barrel was then used inside of the area where the 55-gal. barrel had been (Site 1AA). Tests 1A and 1B were conducted between 0900 and 1130 hours. Test 1AA was conducted between 1135 and 1330 hours.

SLC Tests 6A and 6B were conducted about 2 meters apart. Test 6A was conducted between 1110 and 1410 hours, 6B between 1420 and 1720 hours of the same day.

Tests 3 and 3A at Lakeview were conducted simultaneously. The 5-gallon accumulator belonged to the Oregon State Health Department. The large regression error primarily relates to only taking two samples. Thus, the regression line is based on the (0,0) intercept and two sampling points, with the result that there is only 1 degree of freedom (n-2).

The Boulder City samples were taken on two different test plots covered with two inches of tailings from Shiprock, New Mexico, uranium mill tailings pile. Although the tests were taken two weeks apart, they were taken on days with similar climatological conditions.

Table 3
Replicate Flux Samples

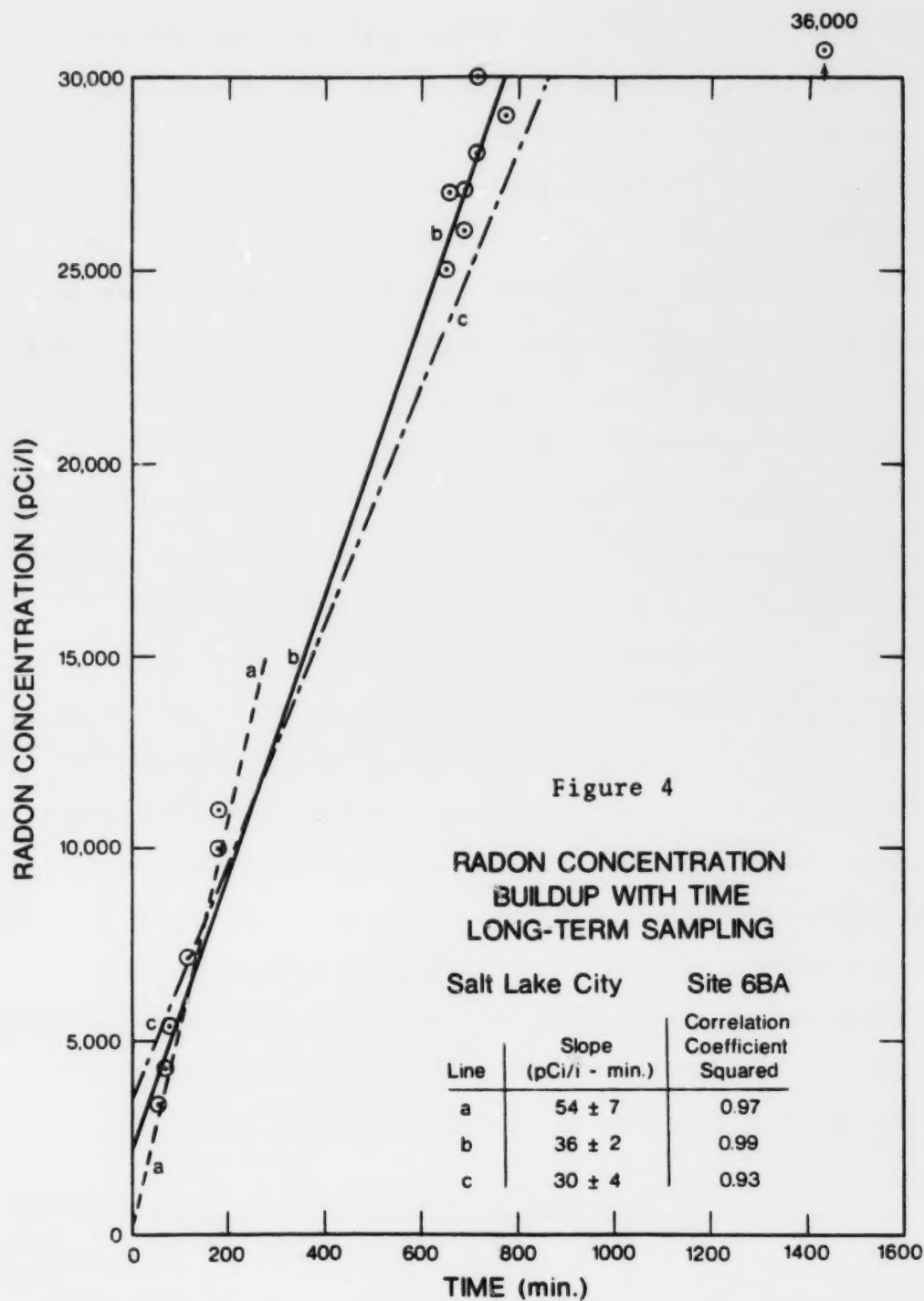
Location	Site Sample No.*	Radon Flux $\text{fCi/cm}^2\text{-sec}$	Percent Error	Value/Mean	Sampling Vessel (Gallon)
Salt Lake City	1A	15.1	20	1.03	55
	1AA	13.0	21	0.89	30
	1B	15.8	54	1.08	30
Salt Lake City	6A	65	21	1.09	55
	6B	54	29	0.91	55
Lakeview	3	0.37	55	0.99	30
	3	0.38	130	1.01	5
Boulder City	1	1.10	10	1.00	30
	2	1.09	3.7	1.00	30

*Salt Lake City Site 1AA was actually located inside of the area covered by Site 1A. The other duplicate measurements were based on adjoining areas which had similar physical characteristics; e.g. soil moisture, radium content, etc.

The y-axis (pCi/l) intercepts and 95 percent Confidence Level (CL) error terms are given in Appendix B. With several minor exceptions, the error terms are such that the intercepts are not significantly different from zero at the 95 percent CL. In all cases the intercepts are less than the initial radon concentration (not given in Appendix B) taken roughly 30 minutes after barrel emplacement. Thus, it is reasoned that the sites were not significantly disturbed and that the linear regression line is valid. It is concluded that the y-axis intercepts, excluding several notable cases, are not significantly different from zero.

The site locations designated by a prime (e.g., Salt Lake City, 6BA') are locations where the sampling barrel was left in place over night, and measurements were taken the next day. Most of these data sets indicate y-axis intercepts significantly different from zero and a decreased exhalation flux with increased measuring time. The intercept of the line also increases, indicating that the later points not only decrease the slope (the exhalation flux), but cause the line to deviate from the (0,0) intercept.

Figure 4 presents the data for Salt Lake City Site 6BA. Several lines are shown. One for the daytime measurements (line a), one including the daytime and nighttime measurements (line b), and a line also including a measurement from the next morning (line c). It is apparent that the data sets which include the readings taken at night should not be



fitted with a single straight line. Rather, they should be fitted with a sequence of lines: one for the initial daytime values and two for the nighttime segments. This implies a change in the diurnal radon flux. Wilkening et al. (1972) indicate there is no significant change in the diurnal flux. Thus, it appears that these long term measurements involve conditions that violated the assumptions inherent in the concepts of linear accumulation of radon.

Although soil gas concentrations were not measured, they can be estimated from calculations and measurements of other investigations. Data from the present study indicated average parameters for Salt Lake City, Site 6BA of 1000 pCi/g of radium, porosity 0.38, and dry bulk density of about 1.4 g/cm³. Culot et al. (1973) indicate an emanating power (EP) of 20 percent for tailings. An estimate of the maximum radon concentration in soil gas can be made by using the above parameters and assuming all the radon remains in the soil volume where it is produced. This is largely representative of the situation at a depth of several meters, where the radon diffusing out of a volume is largely replaced by radon diffusing in from the surrounding media. The maximized estimate is 700,000 pCi/l.* Vohra et al. (1964) indicate normal soil

$$\frac{*1000 \text{ pCi Ra}}{\text{g}} \times \frac{2.1 \times 10^{-6} \text{ pCi/sec of Rn}}{\text{pCi of Ra}} \times \frac{1.4 \text{ g}}{\text{cm}^3} \times 0.2 \text{ EP}$$

$$\times \frac{\text{Decay Const.}}{2.1 \times 10^{-6} \text{ sec}^{-1}} \times \frac{\text{Soil Volume}}{0.38 \text{ void volume}} \times \frac{1000 \text{ cm}^3}{\text{liter}} = 737,000 \text{ pCi/l}$$

gas concentrations up to 1000 pCi/l, which relates to 1,000,000 pCi/l for tailings.* Kraner et al. (1964) report values of over 300 pCi/l at a depth of 1 meter or roughly 300,000 pCi/l for tailings. Information from Kraner et al. (1964), and Aleksexev et al. (1957) indicate soil gas concentrations at 10 cm are roughly 10 percent of those at depth, or about 50 to 100,000 pCi/l for uranium mill tailings. Wilkening et al. (1972) report a value of 17 pCi/l of radon at 13-cm depth in soil with a radium concentration of 1.25 pCi/g. This relates to about 15,000 pCi/l for tailings which contain 1000 pCi/g of radium.

From the foregoing it is evident that accumulated concentrations associated with long-term flux measurements (up to 30,000 pCi/l) were a significant fraction of the soil gas concentrations and that diffusion was impeded.

The radon in the surface soil gas is the immediate source of the radon in the accumulation vessel. Thus, the radon concentration in the surface soil exceeds that in the barrel. During sampling periods when the accumulated radon concentration reaches a significant fraction of the radon concentration in the surface soil gas, there is an increase in the radon concentration of the surface soil gas. Radon not only diffuses

*Assume a linear relationship; i.e., 1000 pCi/l per 1 pCi/g of Ra in soil times 1000 pCi/g of Ra in tailings, equals 1,000,000 pCi/l.

out of the soil with the soil gas, but back into the ground. The end result, shown in Figure 4, is a decrease in the radon flux, as evidenced by the decrease in the slope of the curves for increased sampling times.

DISCUSSION AND CONCLUSIONS

Radon exhalation rate (flux) measurements were made at four uranium mill tailings sites using the accumulation technique, similar to that used by Wilkening et al. (1972). This report describes the equipment and technique used, and the verification of the technique.

Four replicate sets of samples indicated variations from the mean of 10 percent or less. The maximum spread of the results was 20 percent. This variation is similar to and generally less than the 95 percent confidence level (CL) errors calculated for the regression line analyses for the individual flux measurements (see Appendix B). The calculated 95 percent CL uncertainties of the y-axis intercepts of the regression lines were greater than the intercepts, indicating that the intercepts were not significantly different from zero. This signifies that the site conditions affecting the flux were not markedly altered by the measurement techniques and sampling periods of several hours duration.

The results for measurements made over long periods of time (over 8 hours or overnight) indicated a decrease in the flux, i.e., a shift in the slope of the regression line.

Furthermore, the intercepts of the regression lines were also statistically different from zero, indicating a change in the site characteristics during the measurements. Calculations indicated that the accumulated radon concentrations were approaching the soil gas concentrations. Thus, the depth profile concentration of the soil gas was affected since the surface boundary layer was no longer an effective infinite sink.

Several limited experiments to assess the adequacy of mixing of the accumulated radon/air mixture indicated that there were no problems, especially during the day, with solar heating of the accumulation barrel. It appears to be prudent to insure mixing during night time sampling conditions.

Solar heating of the accumulation barrel causes significant temperature increases (8°C) of the accumulated gases. The temperature increase and fluctuation cause an associated pressure or volume fluctuation which may affect the radon flux. The temperature was initially controlled by placing wet towels on the accumulation vessel to provide evaporative cooling. In several instances water dripping from the barrel wetted the surface of the ground under the barrel. Since moist soil reduces the radon diffusion coefficient and thus the flux (Tanner, 1964), results had to be corrected or discarded. In later tests, temperature control was more successfully accomplished by insulating the barrel with foam rubber or polyurethane. Although specific measurements were not made to assess interferences in the radon flux

measurements as a result of temperature increases in the sampling container, it appears to be prudent to control the accumulation vessel temperatures so as to minimize pressure or volume changes.

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Appendix A

Calculations

Conversion of Counts per Minute

in a Cell to pCi/l

The radon concentration in pCi/l is calculated from the following equation:

$$\text{pCi/l} = \frac{\text{net counts per minute}}{\text{C. F.} \times V}$$

Where:

C. F. = the cell factor (counts/minute per pCi of radon standard).

V = the cell volume, 0.125 liter.

Thus, with a cell factor of 4.6 counts/min per pCi, one count per minute corresponds to 1.7 pCi Rn/l.

The cell factor can also be directly related to the cell counting efficiency and volume.

$$\begin{aligned} & \frac{\text{Counts/min}}{\text{Cell}} \times \frac{\text{Radon alpha}}{3 \text{ radon and progeny alphas}} \times \frac{\text{Cell Efficiency}}{0.7} \\ & \times \frac{\text{Cell Volume}}{0.125 \text{ liter}} \times \frac{\text{pCi}}{2.22 \text{ dis/min}} = \frac{1.7 \text{ pCi/l}}{\text{count/min}} \end{aligned}$$

The radon concentrations were converted to standard temperature and pressure, and corrected for any decay between collection and counting of the sample.

Regression or Least Squares Calculations

The regression analyses or least squares analyses were performed using the standard Hewlett Packard statistical packages. The calculation techniques are the same as those given by Natrella (1963) and Remington and Schork (1970).

The slope b is equal to:

$$b = \frac{\sum xy - \sum x \sum y / n}{\sum x^2 - (\sum x)^2 / n}$$

The intercept a is equal to:

$$a = \bar{y} - b\bar{x} \text{ (pCi/l)}$$

Where:

x = the time of radon accumulation in minutes

y = the accumulated radon concentration in pCi/l

$\bar{x}$ and $\bar{y}$ = the average x and y values.

The correlation coefficient, r , is:

$$r = b \frac{S_x}{S_y}$$

Where:

S_x^2 and S_y^2 are the x and y variances, respectively.

For example:

$$S_x^2 = \frac{\sum x^2 - (\sum x)^2 / n}{n-1}$$

Where n is the number of values.

The variance for the slope is:

$$S_b^2 = S_{yx}^2 / S_x^2 (n-1)$$

Where S_{yx} is the standard error of estimate, or:

$$S_{yx}^2 = \frac{(n-1)}{(n-2)} (S_y^2 - b^2 S_x^2)$$

The variance for the intercept is:

$$S_1 = \frac{S_{yx}^2}{(1/n - \bar{x}^2/S_x^2) (n-1)}$$

The appropriate t value for various confidence levels is for $n-2$ degrees of freedom.

Appendix A
Radon Flux Data

(Error terms at 95% Confidence Level)

(r is the correlation coefficient)

LINEAR REGRESSION OF DATA

Sampling Location (Site Number)	Radon Exhalation Rate $\frac{\text{pCi}}{\text{cm}^2\text{-sec}}$	Error (Percent)	r^2	y-Axis Intercept (pCi/l)	Intercept Error (pCi/l)	Radon Counting Error (Percent)	Number of Samples	Number of Sampling Time (Minutes)
Shiprock, NM								
1 "uncovered"	59	25	0.97	660	1100	< 5	6	180
2 "	132	21	0.99	1900	1500	< 5	4	120
3 "	93	5.3	1.00	290	310	< 5	6	150
4 Stabilized	128	12	1.00	-130	620	< 5	3	90
5 "	168	19	1.00	-250	1300	< 5	3	90
6 "	220	24	0.99	440	2100	< 5	3	90
7 "	141	21	1.00	240	1200	< 5	3	90
8 "	44	99	0.90	360	1700	< 5	3	90
Salt Lake City								
LA Crusted Area								
1AA "	15.1	20	0.99	-40	160	< 4	4	120
1F "	13.0	21	0.99	-19	520	< 7	4	120
2 "	15.8	54	0.92	-14	160	< 4	4	115
2' "	15.1	13	1.00	12	120	< 4	5	145
2A Crust Broken	11.3	12	0.98	192	710	< 4	8	1350
3 Dirt Cover	37	27	0.98	68	500	< 4	4	120
4 "	10.8	58	0.99	-29	150	< 6	5	150
5 "	60	15	0.99	130	750	< 3	4	150
5' "	24.7	25	0.98	-130	420	< 4	4	150
	8.3	17	0.97	810	720	< 4	7	1275

Appendix B (Continued)
 Radon Flux Data
 (Error terms at 95% Confidence Level)
 (r is the correlation coefficient)

LINEAR REGRESSION OF DATA

Sampling Location (Site Number)	Radon Exhalation Rate $\frac{fCi}{cm^2-sec}$	Error (Percent)	r^2	Intercept (pCi/l)	Intercept Error (pCi/l)	Radon Counting Error (Percent)	Number of Samples	Time of Sampling (Minutes)
6A Bare Tailings	65	21	0.99	300	1164	<2	4	180
6B "	54	29	0.97	540	1200	<2	6	180
6B' "	35	6.1	1.00	1700	890	<2	8	1114
6BA "	78	13	0.97	220	780	<2	12	180
6BA' "	51	5.1	0.99	2100	850	<2	21	776
6BA'' "	43	13	0.93	3600	2000	<2	22	1432
8 Sewage Sludge	49	4.5	1.00	131	320	<2	6	310
9 "	32	3.7	1.00	-3	110	<4	5	270
10 Bare Tailings	10	35	0.97	-25	500	<5	4	191
11 "	24	9.4	1.00	22	130	<5	4	132
	15.5	23	0.98	120	280	<4	4	159
Lakeview, Oregon								
1	1.53	32	0.97	-7.4	51	<8	4	226
2	1.59	8.8	1.00	-2.9	12	<6	4	220
3	0.37	55	0.92	1.2	19	<13	4	180
3A	0.38	130	0.99	2.4	68	<10	2	123
3B	1.10	6.1	1.00	0.17	4.8	<7	3	150
4	1.37	38	0.96	13	70	<5	4	313
Old Pond Area								
5	0.30	8.4	1.00	1.12	2.6	<10	4	230
8	0.076	39	0.96	1.03	3.2	<20	4	215
9	3.1	37	0.96	1.53	120	<5	4	295
10	1.88	26	0.98	3.14	53	<7	4	177
Boulder City, NV								
1 Uncovered	1.10	10	0.99	-10	18	<10	6	330
2 Uncovered	1.09	3.7	1.00	0.11	1.6	<18	4	96
RC 7 Sulfur Cover	0.77	31	0.93	25	40	<5	6	300
8 Sulfur Cover	0.077	30	0.95	0.71	2.8	12 - 40	6	268
Av. Background	0.05							